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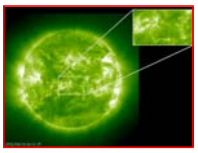

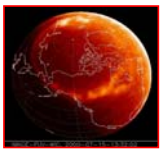

Space Weather

Daniel .N. Baker (APS, Physics)
Chair, Committee on Solar & Space Physics (NAS)
Co-Director, NSF Center for Integrated Space Weather Modeling
Director, Laboratory for Atmospheric and Space Physics
University of Colorado, Boulder

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Understanding of Sun-Earth Connections

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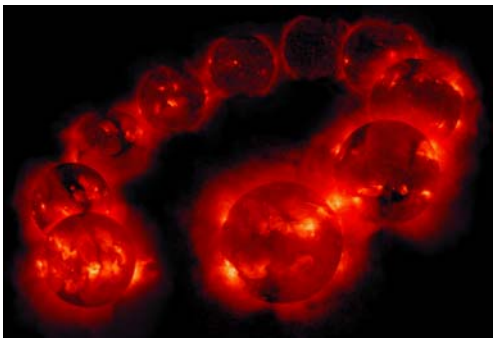
Yohkoh Soft X-rays: The 11-Year Solar Activity Cycle



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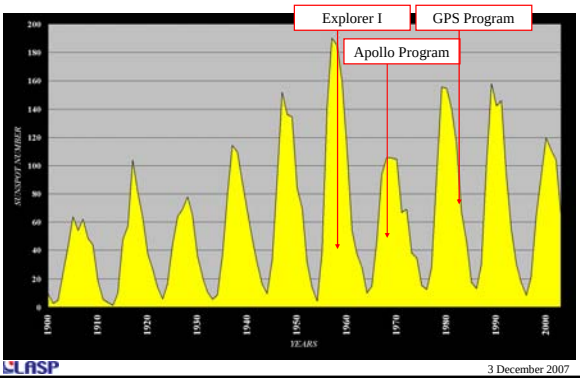
Annual Sunspot Number: 1900-2003



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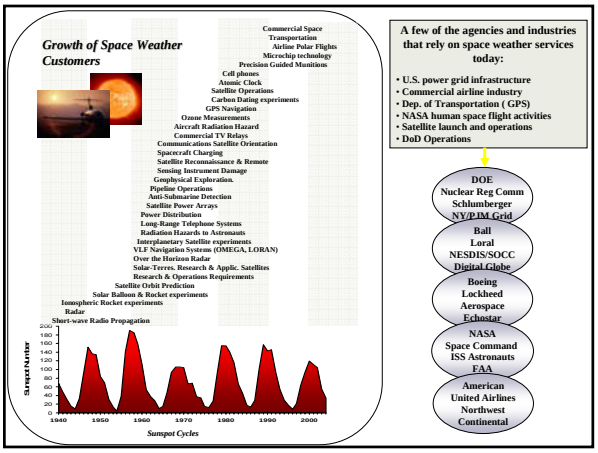
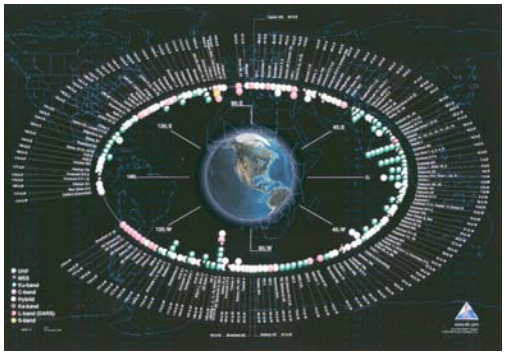


Civilian Spacecraft at Geostationary Orbit



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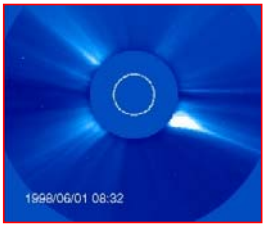
The Disturbed Solar Wind: Coronal Mass Ejections (CMEs)



- Occur most often near the peak of the Sun's 11-year activity cycle
- Propel >10^9 tons of matter into interplanetary space
- Can travel at speeds exceeding 2000 km/s
- Drive interplanetary shocks
- Can trigger geomagnetic storms when they impact Earth's magnetosphere

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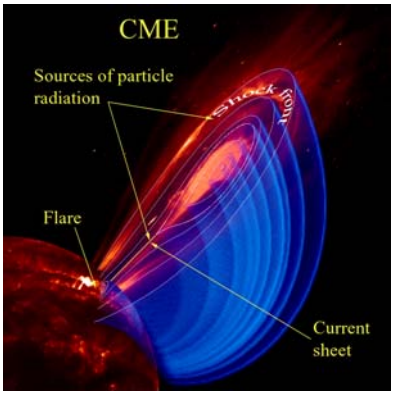

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Coronal Mass Ejection - Earth Impact

Courtesy of NASA

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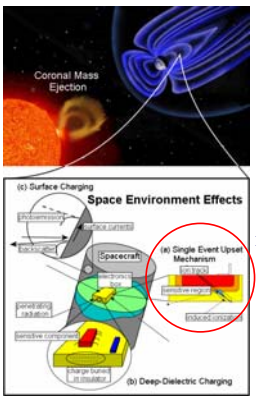

High-Energy Ion Effects

D.N. Baker "How to Cope with Space Weather," *Science*, 297, 1486, 2002

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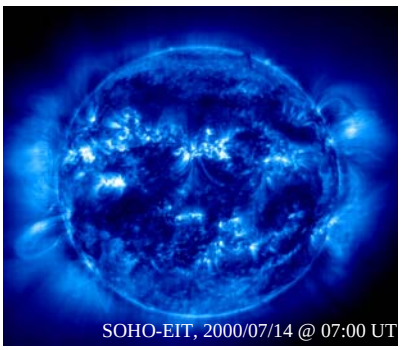
The Active Sun: July 2000



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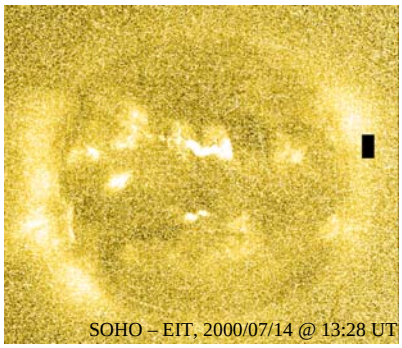
Background Produced by Solar Energetic Particles



SOHO – EIT, 2000/07/14 @ 13:28 UT

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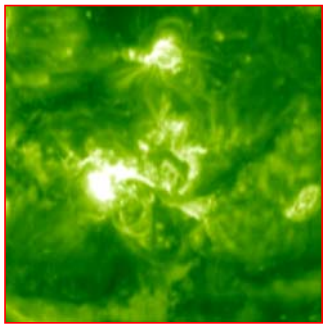
SOHO: Pictures of the Sun—Halloween 2003



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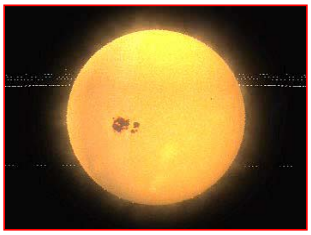
The Halloween Storms in the Heliosphere



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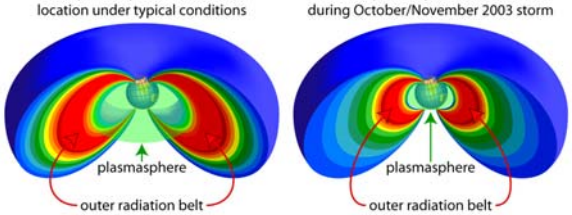
Dramatic Van Allen Belt Changes

a. Normal plasmasphere/radiation belt location under typical conditions

b. Distorted plasmasphere/radiation belt during October/November 2003 storm



D. N. Baker et al., Nature, December 2004

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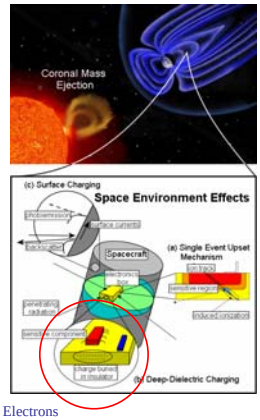

High-Energy Electrons

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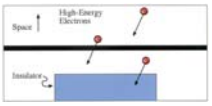
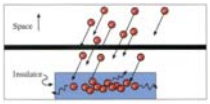
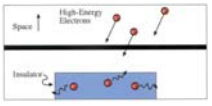
High-Energy Electrons: Deep-Dielectric Charging



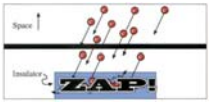
1. Electrons bury themselves in the insulator



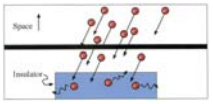
4. Electrons build up faster than they leak off



2. Electrons slowly leak out of the insulator



5. Discharge (electrical spark) that damages or destroys the material



3. Influx of electrons increases to levels higher than the leakage rate

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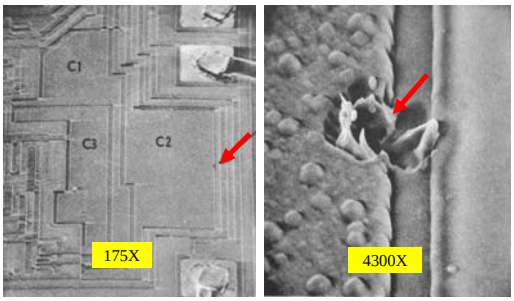
Electrostatic Discharge (ESD)

- Definition:
  - A transfer of electrostatic charge between bodies at different electrostatic potentials caused by direct contact or induced by an electrostatic field.

ESD Damage

HA-2700 surface damage in the C2 MOS capacitor
(Courtesy of JPL)



News Accounts of Galaxy-4 Failure


Dangers lurk in growing reliance on satellites

Satellite's death puts millions out of touch

PanAmSat Scrambles To Restore Service

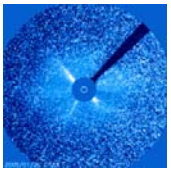
The Day the Beepers Died

It is not always possible to prove that conditions in the space environment cause problems with communication devices such as cell phones and pagers, but it is one explanation.

Satellite Industry

Solar storm warnings and alerts uses:

- Instruments and/or spacecraft turned off or safed
- Maneuver planning
- Anomaly assessments
- Orbit determination accuracy



- Increased spacecraft and instrument monitoring for health and safety during solar storms

"The SEC provides an invaluable and essential service to space operators" – Director of DG Space Operations – 22 March 2006

Satellite Launch operations

Lockheed Martin's Atlas, Titan, and Athena rockets have a launch red line condition of 100 pfu at > 50 MeV

Launch of Kodiak Star Postponed Due to Solar Flare

The launch of Kodiak Star has been postponed for at least an additional 24 hours. A solar flare of significant magnitude occurred this morning at 7a.m ADT (11 a.m. EDT) producing a "proton flux" exceeding the allowable launch criteria for the Athena I. These high levels of charged particles can cause a "data upset" in the launch vehicle guidance system affecting its reliability. - Sep 2001

Human Space Flight

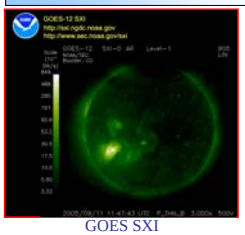
- Shuttle missions and EVAs require particular attention. Note: *The EVA-1 hr briefing is the last opportunity to abort an EVA due to space weather. (>30 MeV events are primary concern)*

NASA SRAG will report to Mission Control when:
>K6 observed *(1 observed period after decay)*
>M5 observed
Protons (All >100 MeV events).

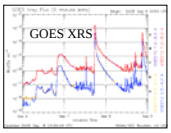
- Electron belt enhancements can delay or postpone an EVA.

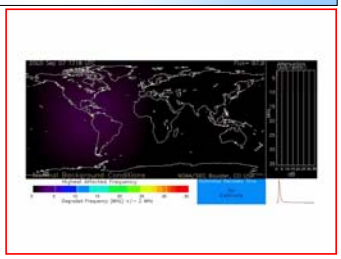
ISS: 50 pfu at > 100 MeV - shutdown the robotic arm
100 pfu at > 100 MeV - alert Mission Control. The Flight Team will start to evaluate a plan to shutdown equipment to prevent damage to electronics.
200 pfu > 100 MeV - plan is implemented

Airlines



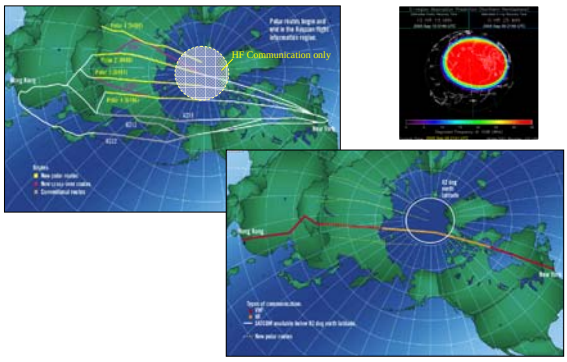
GOES SXI





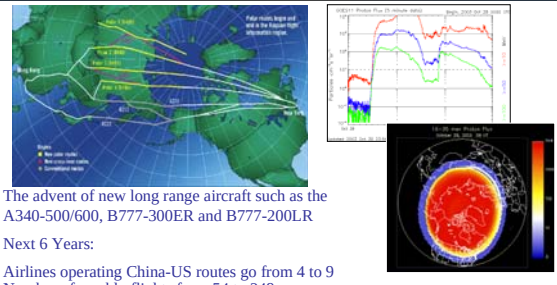
Loss of High Frequency (HF) communications during a solar flare.
The night-side of the Earth is unaffected

Image from NASA SOHO Satellite



- Polar flights departing from North America use VHF (30-300 MHz) comm or Satcom with Canadian ATCs and Arctic Radio.
- Flights rely on HF (3 – 30 MHz) communication inside the 82 degree circle.

Aviation Growth…



The advent of new long range aircraft such as the A340-500/600, B777-300ER and B777-200LR

Next 6 Years:

Airlines operating China-US routes go from 4 to 9
Number of weekly flights from 54 to 249

Next 12 Years:

1.8 million polar route passengers by 2018

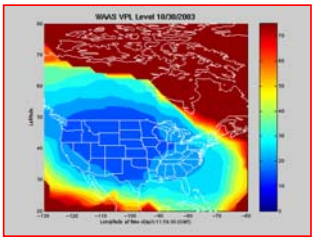
Global Positioning System Customers

- Deep-sea drilling operations
- Surveying companies—land surveying, topographic work, and property boundary analysis
- FAA WAAS (Wide-Area Augmentation System)
- Various DoD operations

Wide Area Augmentation System (WAAS)

Ionosphere Disturbances impact vertical error limits, defined by the FAA's Lateral Navigation Vertical Navigation (LNAV/VNAV) specification to be no more that 50 meters.

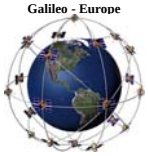
Commercial aircraft unable to use WAAS for precision approaches.



GPS Growth

Global Positioning System used: In-vehicle navigation systems, railway control, highway traffic management, emergency response, commercial aviation, and much more…

NAVSTAR - USA
GLONASS - Russia
Galileo - Europe



GPS Global Production Value—expected growth:
2003 - $13 billion
2008 - $21.5 billion
2017 - $757 billion
Industrial Technology Research Institute (ITRI) – Mar 2005

Space weather creates positioning errors larger than 50 meters
—A mid-latitude problem (where most users reside!)

Electrical Power Grid…

The grid is becoming increasingly vulnerable to space weather events *Future Directions in Satellite-derived Weather and Climate Information for the Electric Energy Industry – Workshop Report Jun 2004*

"…blackouts could exceed even that of the very large blackout that occurred in August 14, 2003. And there is no part of the U.S. power grid that is immune to this… we could impact over 100 million population in the worst case scenario." John Kappenman - before U.S. House Subcommittee on Environment, Technology & Standards Subcommittee Hearing on *"What is Space Weather and Who Should Forecast It?"*

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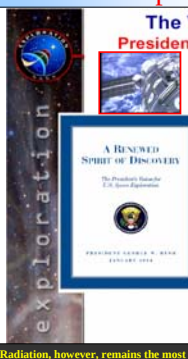
Space Exploration…

The Vision for Space Exploration
Presidential Direction to NASA, January 2004



- Implement a sustained and affordable human and robotic program to explore the solar system and beyond
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

"Radiation, however, remains the most vexing and difficult issue."
Dr. Laurence R. Young, MIT – Testimony to US House of Representatives, Committee on Science Hearing on Perspectives on the President's Vision for Space Exploration (Mar 2004)

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Cover design by Timothy Warchocki.
Image courtesy of NASA

AD HOC COMMITTEE ON THE SOLAR SYSTEM RADIATION ENVIRONMENT AND NASA'S VISION FOR SPACE EXPLORATION: A WORKSHOP

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Radiation Risks

- Carcinogenesis
  - Leukemia
  - Solid Cancers
  - Age/Gender Differences
- Degenerative Tissue Effects
  - Heart Disease
  - Cataracts
  - Respiratory Disease
  - Digestive Diseases
- Damage to the Central Nervous
  - Motor Skills
  - Behavior
  - Accelerated Aging
- Acute Risks
  - Death
  - Vomiting/Nausea

Potential Outcomes

- Mortality: Reduced Lifespan
- Mortality: In-flight (Acute from SEP Events)
- Performance Degradation:
- Morbidity: Post-Flight

Figure 1.2

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Task Statement

An ad hoc committee of the Space Studies Board sponsored a cross-disciplinary workshop on the radiation environments in the inner solar system (1-1.5 AU) and their effects on astronauts and operational systems in space. The workshop consisted of overview talks and group discussions in the following areas:

- Characterization of the heliospheric radiation environment as understood to date, including required data sources
- Physical mechanisms of energetic particle acceleration and transport in the heliosphere as understood to date
- Radiation health hazards to astronauts
- Radiation effects on materials and spacecraft systems
- Mitigation techniques and strategies, including forecasting and operational schemes

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Workshop Goals

- The objectives of the workshop were to:
  - Increase awareness and understanding of the complex array of solar and space physics issues pertinent to the environments of Earth, the Moon, and Mars
  - Identify compelling research goals necessary to ensure the success of the Vision for Space Exploration in these environments
  - Discuss the directions that research in these fields should take over the coming decades in order to achieve these goals.

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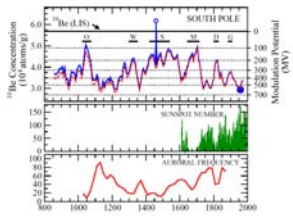
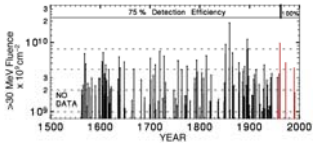
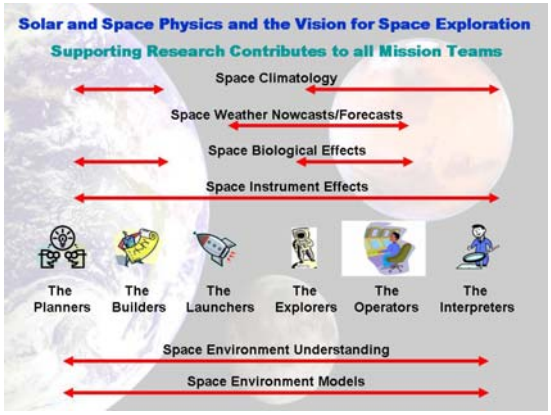


^{10}Be concentrations measured in ice core samples from the South Pole provide a record of the variability in the GCR flux at 1 AU for the period 850 CE to 1958 CE. Intensities are highest during secular minima in solar activity, as denoted in the top panel by the letters and bold horizontal bars and indicated in the second and third panels by the sunspot number and auroral frequency. respectively. (O = Oort minimum; W = Wolf minimum; S = Spoerer minimum; M = Maunder minimum; D = Dalton minimum; and G = Gleissberg minimum) [from *McCracken et al.*, 2004]



Spikes in the NO_3 concentration in Greenland ice core samples converted to proton fluences (black vertical lines) document the occurrence of large fluence solar energetic particle events over a period of nearly four and a half centuries beginning in 1561. Proton events that were detected directly between 1965 and 2000 are indicated by the red lines. [from *Smart et al.*, 2005, based on *McCracken et al.*, 2001]



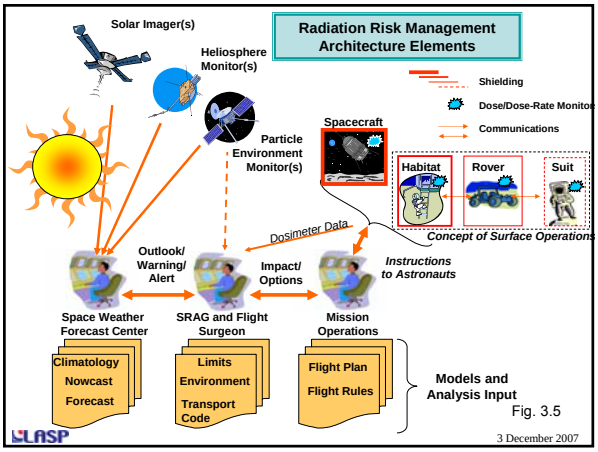
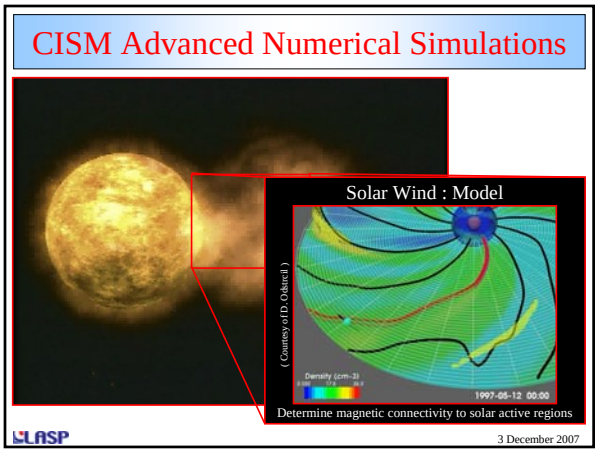


Fig. 3.5



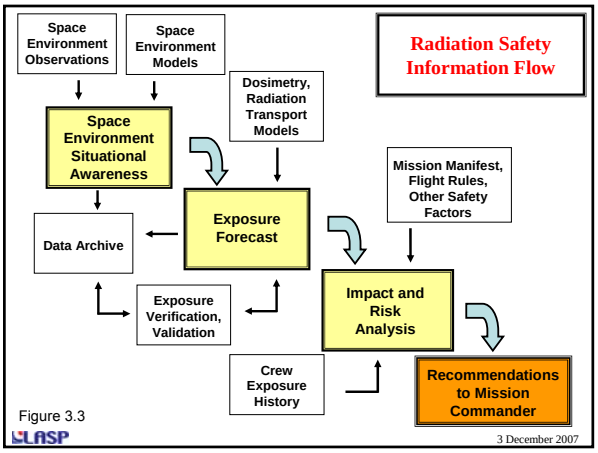
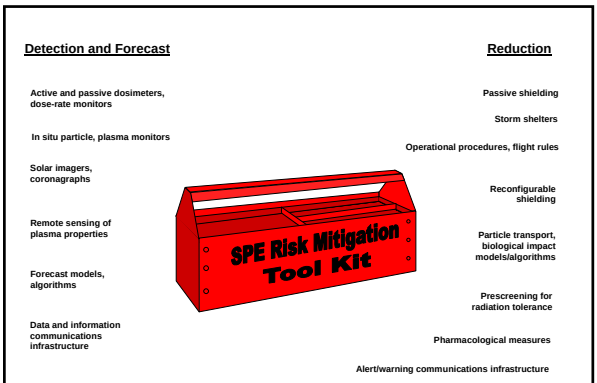


Figure 3.3

Thanks—Questions?



Systems Approach to Radiation Risk Management

- It is critical to decide at the outset what the radiation risk mitigation strategy will be and then to integrate this strategy into the mission concept early in the design phase
- The generic elements of a radiation risk mitigation strategy include space environment situational awareness, radiation exposure forecasting, and exposure impact and risk analysis
- These elements combine to generate recommendations to the mission commander, who has the responsibility for keeping the radiation exposure as low as reasonably achievable

Generally Agreed Points

Among the points that the workshop participants agreed on were the following:

- Developing timely predictions of the radiation environment is a complex task whose components vary depending on the timescale considered and on the mission characteristics
- Delivering timely predictions requires advances in basic space and solar physics, development of observational assets, improved modeling capabilities, and careful design of communications
- The space operations community—that is, those who plan and manage human spaceflight missions—must be informed about these advances in understanding and expanding capabilities so that operators can take advantage of advances
- In some cases operational tools (i.e., tools for space operations) must be developed or adapted from scientific analytical tools and converted to real-time reporting tools; the transition from research to operations is a very challenging task

Uncertainties

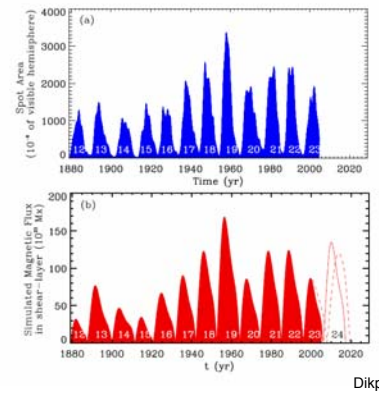
- The large uncertainties in space radiation and biological effects that exist at present increase the cost of missions owing to the large safety margins required as a consequence
- These uncertainties also limit the ability to judge the effectiveness of risk mitigation methods, such as improvements in shielding or biological countermeasures.
  - Operational measures and radiation shielding are currently the main means of reducing radiation risk
  - Improved biological markers have the potential to enable improved early diagnostics
  - Discovery of means of biological prevention and intervention may lead to significantly more powerful methods, including better radioprotectants, to overcome the biological consequences of exposure to radiation
  - Continued basic research has the potential to address all of these key issues effectively

Need for Multidisciplinary Approach

- The workshop effectively recognized that a multidisciplinary approach to defining the challenges of human exploration is required.
- No single National Academy of Sciences decadal survey or combination of surveys provides the type of advice needed for the new programs that are anticipated under the Vision for Space Exploration.
- Also, no single scientific or engineering discipline can provide the expertise and knowledge necessary to solve these problems optimally.

Historical Record

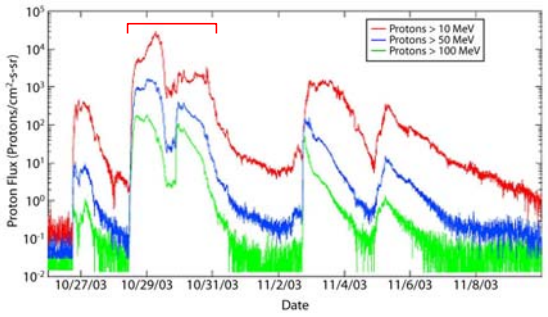
- Recent studies of historical data from polar ice core samples suggest that solar events much larger than the August 1972 event have occurred during the past several hundred years.
  - The largest of these events appears to have been the Carrington event of 1859. Estimates of possible organ doses from an event of this magnitude (~4 times larger than occurred in August 1972) indicate that substantial shielding would be needed to protect human crews in space.
  - Astronauts performing extravehicular activities in space or surface exploration activities on the Moon during an event of this magnitude could receive potentially lethal exposures.
  - Because NASA is contemplating stays on the lunar surface that may eventually last up to 6 months, there is a much higher probability of crews being exposed to a significant solar event than during the much shorter Apollo missions (which lasted no longer than 2 weeks from launch to landing).
- The GCR radiation environment at 1 AU appears at present to be relatively "mild." The historical record suggests that this is unusual and that if this mild interregnum ends, there might be significant consequences for human exploration.



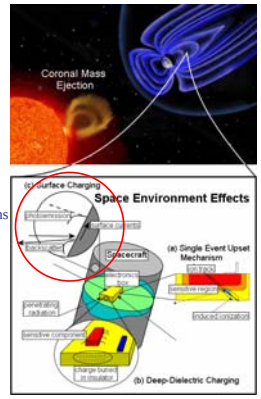
Dikpati et al. (2006)

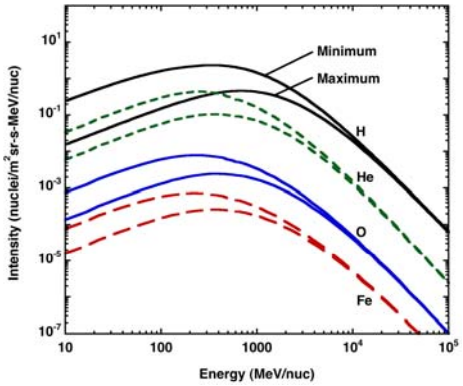
GEO Solar Particle Measurements

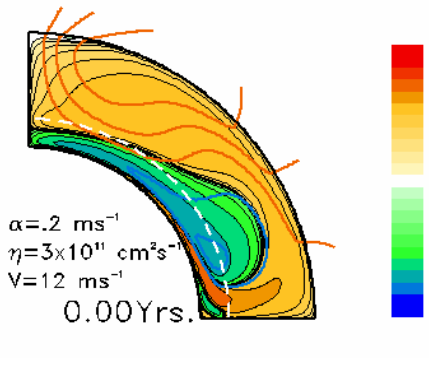
Period of main DoD s/c anomalies



Low-Energy Electrons







Task Statement (2/2)

The workshop will bring together experts from a variety of disciplines to identify open questions that will determine the direction of future research on the above topics. Participants will consider in particular the extent that questions in the areas above can be answered by the focused application of current understanding in the relevant physical, biological, and technological fields, and the extent to which basic research will be required to provide the requisite answers. The workshop will concentrate not only on application of current knowledge, but on the basic research into fundamental physical processes that will be necessary for mitigation of the hazards posed by the radiation environment in which manned expeditions to the Moon and Mars will take place. Given the interdisciplinary nature of the workshop, care will be taken to ensure that the highly specialized topics are presented on a level that will be understandable and useful to the members of the various research communities represented at the workshop.

A report of the workshop will be prepared by this organizing committee.